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DEVELOPMENT OF A STOCHASTIC SIMULATION MODEL FOR PERFORMANCE EVALUATION

E. Gordon and P. G. Freese, *Aerojet ElectroSystems Company, Azusa, California*

ABSTRACT

Simulation played a vital role in the evaluation of the performance of an extremely accurate attitude determination system before it was built and flight tested. This attitude determination system uses a high-sensitivity star sensor. The sensing element is an electron multiplier phototube which responds to incident radiation within a few nanoseconds. This system, with time constants dispersed over more than ten orders of magnitude, was simulated using a set of programs in which the effects derived from the shorter-time constant simulations are explicitly represented in the next model up. This paper describes the development of a representation of the stochastic effects in a manner usable for the models.

INTRODUCTION

Aerojet ElectroSystems Company has developed a high-accuracy attitude-determination system for space applications. The system contains a high-sensitivity star sensor and related electronics on board the spacecraft, producing data which is processed on the ground to accurately determine the attitude of the spacecraft. This paper addresses the development of simulation models used to demonstrate feasibility and evaluate the performance characteristics of the techniques being developed before the system was built and flight-tested. Since the development of the simulation paralleled the development of the hardware and software, early simulation results provided useful guidance for the detailed design.

The basic sensing element of the star sensor is an electron multiplier phototube. The response of the phototube to star signals is transmitted to a ground station for processing without significant loss in accuracy. In the ground data processing, the information received regarding star sightings is compared with

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predictions based upon the accurately known star locations in celestial coordinates to determine the orientation of the spacecraft. The essential functions which must be performed by the attitude-determination system are summarized in the following subsections.

Functions Performed On Board the Spacecraft

The star sensor contains a sun shade, a sun sensor and shutter, an optical assembly, a reticle, a phototube, and electronics. The optical assembly collects and focuses the light from stars onto the surface of a reticle. The sun shade attenuates the stray reflections of sunlight within the optical assembly so that stars can easily be detected in the data generated when the sun is not close to the field of view of the optical assembly. The sun sensor provides a signal which causes the sun shutter to close when intense light from the sun can reach the phototube.

Only the light from stars whose focused images fall on a slit in the reticle interact with the light-sensitive cathode of the phototube. The probability that a photon will cause the photocathode to emit an electron is called the quantum efficiency and it is dependent upon the wavelength of the photon. The emitted electron is multiplied in the phototube by secondary emission each time an electron interacts with a dynode. The overall gain of the electron multiplication process in the phototube used is of the order of one million. Because of the rather short duration (tens of nanoseconds) of the anode pulse resulting from the electron multiplication process, a modest amount of additional signal gain in the star-sensor electronics is sufficient to produce a signal from a single emitted electron which is readily detected in the electronics and converted into a normalized output pulse. To simplify the terminology, each anode pulse due to an electron emission from the photocathode is called an event.

The number of normalized output pulses occurring in an interval (called a count cycle) of 140 microseconds duration is determined and the resulting count values are transmitted to the ground for processing. The system was designed based upon a star of sufficient intensity to cause events to occur at an average rate of two hundred thousand per second, i.e., one per five microseconds on the average. Because this average interval between events is long compared to the duration of typical anode pulses, it was possible to make performance and design analyses without getting bogged down by the complications resulting from the interactions in the electronics due to individual events. However, the system performance must be evaluated and demonstrated over the full range of star intensities of interest. The brightest star, Sirius, was expected to yield an average rate sufficient to make the average time between events comparable to the anode pulse duration. Several planets are brighter than Sirius, yielding even lower average times between pulses.

The Model discussed in the following section was developed to simulate the consequences of the interactions between events in the star-sensor electronics. The initial purpose of this simulation model was to evaluate the possible need for higher frequency electronic components in the star-sensor electronics and in the pulse counter, and for refinements in the design to modify its response characteristics when exposed to the light from bright stars. Hence, this simulation was available and the results had been analyzed when the effort to develop an "end-to-end" simulation was initiated. It was clear that costs would be prohibitive if the "end-to-end" simulation included an explicit simulation of the individual events, even at the simplified level of representation used in the Nanosecond Regime Model. One simulation, which represented only one millisecond for the brightest star, had one hundred thousand events and consumed ten minutes of computer time. Fortunately, the single run at that intensity was sufficient to provide the information required for the analytical model of the Nanosecond Regime Model results.

Functions Performed in Ground Processing of the Data

The ground processing of the data starts with the receipt of the data telemetered from the spacecraft. The star-sensor data are separated from the rest of the data stream in a preprocessor which extracts candidate star sightings. The candidate star sightings are extracted from the data stream by the use of a threshold which is dependent upon the average background level.

The star candidates are transferred from the Preprocessor to the computer via a selector channel. The same data channel also contains timing information from which the time of each sighting can be calculated. Since most of the star candidates are background phenomena or dimmer stars not in the star catalog used for attitude determination, most of the candidates are rejected in the computer processing which edits the data. The edited, sighting-time data are the inputs to the Kalman filter which estimates the attitude of the spacecraft.

When the simulation effort described in this paper was initiated, a rudimentary version of the filter had been implemented and was undergoing preliminary development testing. For these tests, star sighting times were computed based upon the star-sensor reticle geometry undergoing motions determined by a spacecraft dynamics simulator. The dynamics simulator represented both the motion of the center of mass of the spacecraft as well as the orientation variations typical of the attitude-control system.

Preliminary analyses of the requirements for the Performance Evaluation Simulation Model quickly led to the conclusion that the primary objective was the determination of how well the filter could follow realistic spacecraft motions. The details of the dynamics simulation were of secondary importance and there was no need to improve on the dynamics simulation available. The much more critical question was the effect of the rather complicated stochastic properties of the star sighting and background data on the dependability and accuracy of the spacecraft attitude determined by the filter. The attitude variations being estimated can be described in terms of time constants of the order of a minute superimposed upon longer-term alignment changes and orbital motion.

The full range of time constants which must be considered in the Performance Evaluation goes from phototube anode pulse durations of a few nanoseconds through the spacecraft attitude dynamics with time constants as long as hours. The development of the simulations which provided the needed results is covered in this report. Because the more slowly varying conditions cannot change significantly in the brief time span encompassed in the Nanosecond Regime Model runs, the model development effort did start with the Nanosecond Regime Model and developed summary relationships useful for the longer time scales.

NANOSECOND REGIME MODEL

There is a non-zero dispersion of secondary electron arrival times due to the variations in the paths the electrons travel and in the details of the electron multiplication process. The dispersion was reported as 10 nanoseconds in Reference 1, and it represents the minimum event duration (anode pulse width) physically possible. The non-zero capacitance in the phototube output wiring and limitations on the frequency response of the output electronics would tend to increase the effective pulse width. The general characteristics of the star-sensor electronics are such that when events are more than 200 nanoseconds apart, the circuitry can easily respond to each event separately. As the events get closer than the time required to handle one event, some of the events will be ignored. The baseline design is able to accept another event 100 nanoseconds after the preceding event is accepted. One question which the Nanosecond Regime Model simulation addressed was the general signal-response characteristics of the baseline circuitry and the effect of exercising some of the design options available.

The logic of the simulation is summarized in Figure 1. IBM's General Purpose Simulation System (GPSS/360), described in Reference 2, was used; it is convenient for models which involve moderately complicated interactions between independent stochastic events. Generation of photons as the result of a Poisson process (characterized as a stochastic process with a constant expected number per unit time) is handled by a single GPSS generate block. The background caused by high-energy (cosmic) protons and (Van Allen) electrons can also be characterized by a Poisson process. Initially, the quantum efficiency of the phototube was modeled using the GPSS conditional transfer block where one minus the quantum efficiency was the probability that the processing of that photon would be terminated. The computer overhead involved in generating and terminating many simulated photons which were terminated without producing useful information was found to be significant. The simulation was more cost-effective when the generation rate corresponded to electrons emitted by the photocathode.

The counter tested in Block 6 is reset for 100 nanoseconds after acceptance of one anode pulse before it is ready to accept another anode pulse. As indicated in Figure 1, either source of pulses can set the counter. Then, pulses from either source cannot get through until the delay is completed. Blocks 2, 5, 10, 15, 20, and 25 are used to generate and output statistical information required for the analysis of the results without having any direct physical counterparts. The logic as shown is for the hypothetical case in which the anode pulse duration is zero. The effect of anode pulse duration was evaluated by adding logic in place of the termination Block 7 to allow for the possibility that the delay is completed after the anode pulse starts, but before the pulse ends.

In the simulation, the basic time interval used by GPSS as the clocktime increment was equal to 2 nanoseconds of system time. Therefore, the count-cycle duration was 70,000 clock times. Typically, five count cycles were simulated at each condition to provide an estimate of the standard deviation in addition to the mean value for each parameter calculated. For most of the simulations, the background expected count rate was one pulse per 20 microseconds. A few cases were run with background levels of five pulses per microsecond.

The effect of anode pulse duration determined by the simulation is presented in Figure 2. The number of events which do not produce normalized output pulses is indicated by the difference between the number of events (photons interacting with the photocathode and causing the emission of an electron) and the value from the response curve for the event-duration considered. For example, with an event duration of 10 nanoseconds, any event starting within the last 10 nanoseconds of the delay shown in Figure 1 would cause an output pulse when the delay is completed. A detailed analysis of the results demonstrated that the ratio of events to outputs, x/y, was equal to the sum of $x(X3/X6)$ and D, a function of the above probability, where X3 is the delay-interval duration, X6 is the count-cycle duration, and x is the expected number of events per count cycle. For values of x less than 2000 events per count cycle, it was found from the simulation results that

$$D = 1 - 5.5\,cx$$

where c is the event duration expressed in milliseconds. Hence, the output count rate,

$$y = x/(1 + EC*x)$$

where EC is the electronics coefficient equal to $(X3/X6) - 5.5\,c$.

The curves shown in Figure 2 are based upon the above relationship for values of x less than 2000 and the smoothed results for x greater than 2000.

At the very low event rates, the standard deviation of the output count rate from its expected value should have the square root relationship typical of Poisson processes. The results of simulations were consistent with the anticipated square root relationship until a maximum value of 15 was reached, thereafter decreasing to zero as the saturation effect indicated in Figure 2 was approached.

The most important result of the studies with the Nanosecond Regime Model was the demonstration that the delay interval duration, X3, had little effect on the amplitude resolution, i.e., ability to distinguish a relative change in the event rate for the star intensities of primary interest. This result supported the adequacy of the baseline design since the important performance parameters could not be significantly improved by any reasonable changes in frequency response characteristics in the star sensor electronics or in the output pulse counter.

Validation of the simulation involves consideration of debugging and verification of the computer program as well as the adequacy of the simulation model to represent the phenomena of interest. Debugging and verification of the computer program was expedited by the fact that the analyst was conversant with the simulation language so that the programming details were checked by both the analyst and the programmer. Further verification was provided by consistency of the results with simplified analyses for limiting cases. It was apparent that the simulation was a highly simplified model of the processes which occur in the star sensor and its electronics. It was anticipated that a more detailed model would be required to cover anode pulse amplitude variations and pulse shape variations. However, when the results demonstrated that pulse duration had little effect within the range of interest, it was obvious that the cost of developing an improved model was not commensurate with the very limited benefits.

The most important result from the perspective of the "end-to-end" simulation was the finding of a relatively simple relationship between event rate and expected output rate for the star intensity range of primary interest. This relationship could be used on a much slower time frame such as the Microsecond Regime Model.

MICROSECOND REGIME MODEL

The Nanosecond Regime Model is primarily concerned with the relationship between light intensity expressed in terms of the expected rate of electron emissions from the photocathode (events) and the statistical properties of the number of counts that would be output by the star sensor electronics per count cycle. The Microsecond Regime Model generates a stream of count values simulating the output from the star sensor. The expected event rate is the sum of the consequences of

1. Thermal or self-emission of electrons by the photocathode and first dynode
2. Interactions with cosmic rays and solar flare protons
3. Bremsstrahlung from trapped (Van Allen) electrons
4. Star signals used for attitude determination
5. Other star signals including unresolved star background
6. Sunlight scattered or reflected by attitude-control-jet effluent and space debris.

The actual number of pulses output by the electronics depends upon the expected event rate and the relationships derived from the Nanosecond Regime Model. The operations within the Microsecond Regime Model can be partitioned into those involved in determining the expected event rate and those involved in determining the count value which will reach the ground station for processing. Longer-term considerations determine where in orbit the spacecraft is at each count cycle, and which portion of the celestial sphere is being scanned. The information is provided to the Microsecond Regime Model in terms of which stars are going to be sighted, the intensity of the signal received, and the time at which the star image impinges on each of the slits in the reticle.

Of the six sources of events, only the first one has stationary statistical properties. All that is required to represent the thermal emission of electrons by the photocathode is the specification of the expected emission rate. The high-energy-particle radiations are characterized in terms of two-level Poisson processes. The higher-level process is the arrival of high-energy particles, with a time between particles for the protons,

$$TNP = -SP \ \ell n \ RU$$

where SP is the expected number of count cycles between particle arrivals and RU is a random number selected from a distribution uniform over the interval zero to one. Note that each time the symbol RU appears, a new sampling from the uniform distribution is selected by a pseudo-random-number generator. A similar expression applies for the time between high-energy electrons, TNE, based upon EP, the expected number of count cycles between electron arrivals.

Although the expected rates of arrival of high-energy particles do exhibit variations with time, the time constants for solar flares and trapped electrons are on the order of hours. The value of SP and EP could have been left unchanged throughout a simulation run. For increased generality, a gradual change in these expected times between particle arrivals was provided by the FORTRAN expression

$$SP = SP(1.0 + PO*MDT)$$

applied whenever a star sighting is processed, where MDT is the number of count cycles since the last star sighting and PO is the relative increase in the expected time between expected particle arrivals per count cycle. A similar expression applies for EP within the parameter EO in place of PO.

Each arriving particle activates a portion of the star sensor near the photocathode, causing a prompt emission of photons followed by a decaying rate of emission as the activated material returns to its normal state (see Reference 3). The expected contributions to the event rates, RP, and due to protons, due to electrons RE, are time varying. The model used is based upon an exponential decay, with a time constant set by an input parameter. It was assumed that, within each count cycle, the variation was small enough so that the average expected rate could be used without worrying about second-order effects due to variations in the expected rate from the average within the count cycle. The exponential decay is computationally convenient since all that is required is a multiplication of the expected event-rate contribution for one count cycle (e.g., RP) by a factor, DP, which is one minus the decay effect, to determine the expected contribution for the next count cycle if no new particles arrive. It was assumed that the initial responses (PN and PE, respectively) due to a newly arrived particle were the same for all particles of a given type. However, that was later changed to an initial contribution selected from an exponential distribution.

$$\Delta RP = -PN \ \ell n \ RU$$

or

$$\Delta RE = -EN \ \ell n \ RU$$

to allow for the energy variation of the particles when it was found that this variation had a significant effect. The effect of scattered sunlight is represented by an exponentially increasing background contribution until a plateau is reached, followed by an exponential decay.

FORTRAN is the language used for the Microsecond Regime Model and all of the subsequent models. FORTRAN was selected since GPSS would have been inconvenient for the star signal representation. One complication arose when very low expected rates were simulated. Since the expected contribution is decreased by applying the factor for decay, when the expected particle arrival rate was much less than one per one hundred count cycles, the expected contribution could get smaller than the smallest positive number normally represented by floating point 10^{-78}, producing underflows and consequent diagnostic messages.

The star-sighting-time information was generated by a companion model. This model used a simulation of the dynamics of the spacecraft and the attitude control system to select the stars to be sighted, and when they will be sighted, from the

Smithsonian Astrophysical Observatory (SAO) catalog available on magnetic tape. This companion model is outside of the scope of the simulation described. It includes provision for representing alignment changes between the star sensor and the rest of the spacecraft, as well as the reticle slit geometry including deviations from nominal. In the processing of each star signal to be used for attitude determination, the Microsecond Regime Model determines the relationship between computed sighting time and computed count-cycle start times. The portion of the star signal expected to occur in each of the count cycles containing the star signal depends upon this relationship as well as the image quality of the optics. The possibility of overlapping star signals is handled by having the allocations and sighting times for the next two star sightings available.

Background contributions are made by stars which are too dim to be handled on an individual basis, plus intermediate brightness stars which do require individual representation. Initially, the intermediate stars were obtained by carrying the SAO catalog two visual magnitude values beyond that of the stars used for attitude determination. This extension of the star catalog consumed more computer time than desired, and the simplified representation of pseudo-random intermediate brightness stars was added, based on the assumption that the image spot size is zero. The interval between intermediate brightness stars, TND, was determined from an exponential distribution in the same manner as that used for particles.

The contributions of dim and intermediate brightness stars were varied, with a portion of the celestial sphere being scanned to allow for the nonuniform distribution of stars. For the dim stars, the expected contribution was varied; for the intermediate brightness stars, the expected interval between stars was varied

The expected event rate in any count cycle was the sum of the expected values for each of the sources. Except when the count cycle contained the signal from a bright star, the expected output count was determined by applying the nonlinearity relationship derived from the Nanosecond Regime Model. With bright stars, the rate of variation in intensity within a count cycle could be significant and the correction for nonlinearity was adjusted for the rapid variation. A random variation sampled from a normal distribution, with standard deviation equal to the square root of the expected value, was added to represent the stochastic variation effect from the Nanosecond Regime Model. If the expected value was more than 225, the standard deviation used was 15. This deviation was used to approximate the complicated behavior of the standard deviation when the events frequently interfered with each other in the star-sensor electronics.

Telemetry transmission errors cause the data value received to be uncorrelated with the value sent. The occurrence of these errors was represented by a Poisson process, with time between errors equal to -TEℓn RU, where TE is the expected number of count cycle between error. The value in error is equal to 4095 * RU to represent a randomly selected 12-bit value.

MILLISECOND REGIME MODEL

The Millisecond Regime Model differed from the Microsecond Regime Model only in the omission of the background which was not in the neighborhood of a star used for attitude determination. The output desired from the model was the stream of data that the preprocessor would select as star candidates, based upon exceeding the threshold applied. Thus, false outputs were added to represent threshold exceedances due to background sources.

The representation of star signals and telemetry errors was the same as the Microsecond Regime Model. The representation of the effect of particle radiation was also the same after the first count cycle contributions from electron and proton radiation. The primary difference between the Millisecond Regime Model and the Microsecond Regime Model is the absence of the previous history, since the count cycles between star signals were not simulated. This omission is computationally important because less than 1 percent of the count cycles have contributions from star signals used for attitude determination.

Results for background radiation obtained from simulations made using the Microsecond Regime Model were analyzed to determine the distribution of peak expected contributions. This peak represents the last particle arrival prior to the star signal. The model then applies a decay for the elapsed time selected from an exponential distribution between the peak value determined and the first count cycle containing the star signal.

The possibility that the star signal would not exceed the threshold applied by the preprocessor was represented by applying a threshold equal to the expected background value, plus a random variation representative of the measured average background determined by the preprocessor, plus an increment applied within the preprocessor.

LONGER-TERM MODELS

The above models were the primary sources of data used for testing the Preprocessor and for testing the software developed to process the data telemetered from the spacecraft. Other studies (including the effort developing the Kalman filter implementation) for determining attitude used only small portions of the data processing software. Therefore, these studies had to be provided with inputs equivalent to those which the attitude determination portion of the computer program under development would use.

The Millisecond Regime Model provides sets of count values representing the signals from star sightings and noise, whereas the Kalman filter used for attitude determination actually receives sighting times of identified stars. The editing of the data to reject background noise exceeding the threshold applied, and to identify the star signal, is performed by logic preceding the filter. The filter handled only sighting times for identified stars. A Second Regime Model was developed based upon results from Microsecond Regime Model and Millisecond Regime Model simulations. Logic was added to calculate the sighting time that the program would determine from the count values provided. Mean and standard deviations were determined over a range of background conditions and star intensities.

For studies of boresight techniques used to evaluate the alignment between the primary sensor and the satellite reference frame defined by the attitude determination process, the more important time constants are on the order of hours. Thus, it is uneconomical to base the simulations on individual star sightings. Instead, the statistical characteristics of deviations from the "known" attitude that was simulated were determined from analyses of the results of the Second Regime Model studies. These statistical variations were the basis for the boresight studies.

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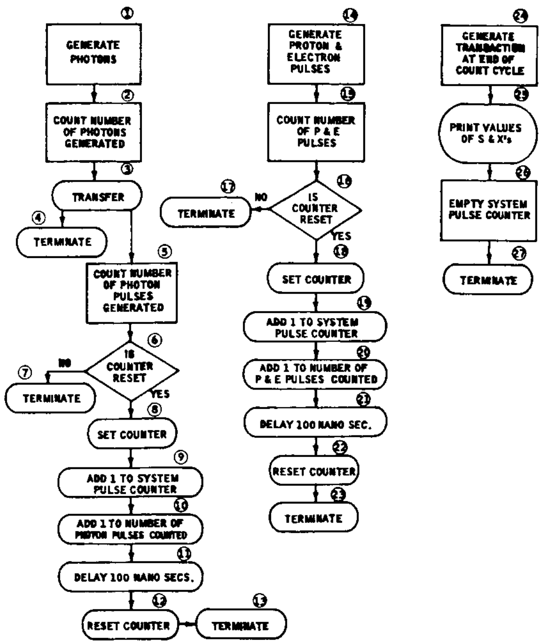

Fig. 1—Nanosecond Regime Model logic

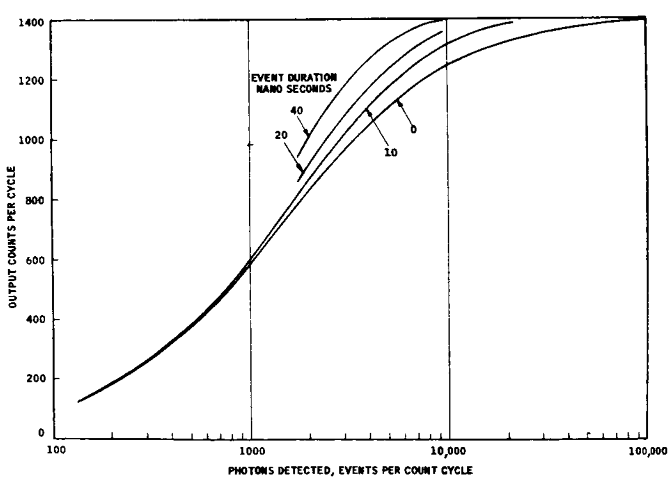

Fig. 2—Effect of event duration